Physics of the Earth and Planetary Interiors 238 (2015) 8–22

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Assimilating lithosphere and slab history in 4-D Earth models

Dan J. Bower [a,*], Michael Gurnis [a], Nicolas Flament [b]

[a] Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA
[b] Earthbyte Group, School of Geosciences, The University of Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form 3 October 2014
Accepted 31 October 2014
Available online 10 November 2014

Keywords:
Mantle structure
Plate history
Mantle convection
Subduction
Dynamic topography
Data assimilation

ABSTRACT

We develop methods to incorporate paleogeographical constraints into numerical models of mantle convection. Through the solution of the convection equations, the models honor geophysical and geological data near the surface while predicting mantle flow and structure at depth and associated surface deformation. The methods consist of four constraints determined *a priori* from a plate history model: (1) plate velocities, (2) thermal structure of the lithosphere, (3) thermal structure of slabs in the upper mantle, and (4) velocity of slabs in the upper mantle. These constraints are implemented as temporally- and spatially-dependent conditions that are blended with the solution of the convection equations at each time step. We construct Earth-like regional models with oceanic and continental lithosphere, trench migration, oblique subduction, and asymmetric subduction to test the robustness of the methods by computing the temperature, velocity, and buoyancy flux of the lithosphere and slab. Full sphere convection models demonstrate how the methods can determine the flow associated with specific tectonic environments (e.g., back-arc basins, intraoceanic subduction zones) to address geological questions and compare with independent data, both at present-day and in the geological past (e.g., seismology, residual topography, stratigraphy). Using global models with paleogeographical constraints we demonstrate (1) subduction initiation at the Izu–Bonin–Mariana convergent margin and flat slab subduction beneath North America, (2) enhanced correlation of model slabs and fast anomalies in seismic tomography beneath North and South America, and (3) comparable amplitude of dynamic and residual topography in addition to improved spatial correlation of dynamic and residual topography lows.

1. Introduction

Plate tectonics is the fundamental Earth sciences paradigm that provides a framework to interpret surface features and the geological record. Processes associated with plate motions and subduction of oceanic lithosphere form island arcs and volcanic belts, accrete material to continental margins, deform plate interiors, and drive vertical motions of ocean basins and continents. Subducting oceanic lithosphere that extends from present-day subduction zones into the upper mantle is revealed by earthquake locations and high seismic velocity anomalies by seismic tomography (e.g., Grand, 2002). Similarly, the circum-Pacific belt of high velocity seismic anomalies in the lower mantle can be correlated with slabs subducted during the Cenozoic and Mesozoic (Richards and Engebretson, 1992). A density model for subducted slabs can explain the degree 4–9 components of the observed long-wavelength geoid (Hager, 1984) and the negative buoyancy of slabs can drive present-day plate motions (Conrad and Lithgow-Bertelloni, 2002).

These first-order inferences suggest an intimate connection between the history of subduction and present-day mantle structure. Seismic tomography reveals lower-mantle slabs that can be used to determine the longitude of paleosubduction zones and therefore potentially constrain absolute plate motions (van der Meer et al., 2010). Intra-Panthalassa subduction zones are predicted by combining the present-day position and timing of formation and accretion of extinct intra-ocean volcanic arcs with a plate reconstruction to compare with seismic tomography (van der Meer et al., 2012). Beneath the Americas, seismically fast anomalies around 800 km depth relate to subduction of the Nazca, Cocos, and Juan de Fuca plates (Ren et al., 2007). The broad sheet-like high velocity anomaly in the lower mantle beneath eastern North America is typically thought to have originated from the Cretaceous subduction of the Farallon plate (Liu et al., 2008; Grand, 2002; vander Hilst et al., 1997), although an alternative hypothesis suggests it is slab that originated from intra-oceanic subduction zones (Sigloch and Mihalynuk, 2013).

* Corresponding author.
E-mail address: danb@gps.caltech.edu (D.J. Bower).

http://dx.doi.org/10.1016/j.pepi.2014.10.013
0031-9201/

The large low-shear velocity provinces (LLSVPs) are long-wavelength structures (~1000 km) at the core-mantle boundary that are positioned at present-day beneath Africa and the Pacific Ocean. The role of paleosubduction in determining the location and morphology of the LLSVPs remains debated. Some models favor substantial mobility of the LLSVPs in response to plate motions (Davies et al., 2012; Zhang et al., 2010; McNamara and Zhong, 2005), while others suggest that LLSVPs are insensitive to Wilson cycles (e.g., Torsvik et al., 2010) and may even organize plate tectonics (e.g., Dziewonski et al., 2010). Broad upwellings can be produced in dynamic models with imposed slab buoyancy flux for the past 300 Myr that share some similarities to the inferred distribution of plumes at the edges of LLSVPs (Steinberger and Torsvik, 2012). Therefore, understanding the dynamic interplay between surface tectonics and lower mantle structure enables us to interpret seismic images as a time-integrated record of an evolving thermochemical mantle. Furthermore, we can elucidate potential connections between surface geology and deep structure such as large igneous provinces derived from deep-seated mantle plumes.

Convection models with data constraints are used to estimate global long-term sea-level change since the Cretaceous by predicting isostatic and dynamic topography to determine the volume of ocean basins (Müller et al., 2008), eustatic sea level (Spasojevic and Gurnis, 2012) and differential, vertical motion of continents (e.g., Moucha et al., 2008; Spasojevic and Gurnis, 2012). Present-day mantle thermal heterogeneity derived from seismic tomography is often used as an initial condition for inverse (backward advection) models (e.g., Spasojevic and Gurnis, 2012) or a present-day constraint for adjoint models (e.g., Bunge et al., 2003; Liu et al., 2008; Spasojevic et al., 2009). Stratigraphic data constrains the vertical motions of North America and provides an estimate of the viscosity ratio across the 660 km discontinuity by associating subduction of the Farallon slab with the widespread flooding of the western interior of North America (Spasojevic et al., 2009).

Convection models can be either entirely physics-based or semi-empirical. Entirely physics-based models honor the physics of fluid flow through conservation laws and are best suited to investigate the fundamental physics of convection in an Earth-like body. Using realistic constitutive relations, they can be used to explore evolving subduction in two dimensions and give rise to asymmetric subduction with slabs that are of the same thickness as the incoming oceanic plate (Burkett and Billen, 2009). However, given the high resolutions required, of the order of 1 km, physics-based convection models require enormous computational resources and so cannot yet be applied to large-scale, three-dimensional and long duration models that would be required to address the spatial and temporal characteristics of subduction preserved in the geological record. By contrast, semi-empirical models impose "known conditions" on the system to ensure that models are consistent with the history of subduction: for example, kinematic boundary conditions are commonly applied at the surface to model plate motions (e.g., Bunge et al., 1998). These models are not physically-self consistent because behavior that is enforced by applied conditions (e.g., plate motions) would not otherwise necessarily evolve naturally from the physics or parameters that the models include. Such models are still computationally expensive albeit feasible with existing technology.

The progressive data assimilation method that we develop here is a semi-empirical approach that can be used to investigate the flow associated with specific tectonic environments, such as back-arc basins and intra-oceanic subduction zones. This enables us to address geological questions at both regional and global scales and compare with independent data at present-day and in the geological past (e.g., topography, geoid, gravity, seismic images, stratigraphy, rock uplift, etc.). Oceanic lithosphere, continents, slabs, and LLSVPs are volumetrically significant components of the mantle buoyancy field and are closely linked to plate tectonic history. Therefore, it is necessary to ensure that the temporal and spatial distribution of these buoyancy sources is consistent with plate history to create 4-D Earth models to compare with other data. Concurrent developments in paleogeographic software such as GPlates (Gurnis et al., 2012) are enabling construction of high temporal and spatial resolution plate history models (Seton et al., 2012) that include deforming regions (Flament et al., 2014). Variants of the assimilation method presented herein have already been incorporated into models to understand the paleogeography of Australia (Matthews et al., 2011), the influence of plate reconstructions on deep Earth structure (Bower et al., 2013), and the topographic asymmetry of the South Atlantic (Flament et al., 2014).

2. Method

We devise our progressive data assimilation method to produce global convection models with prescribed subduction zones that are consistent with an *a priori* plate history model. The method is comprised of four *a priori* data constraints that are applied to the convection model at each time step: (1) plate velocities (including velocities in deforming regions), (2) thermal structure of the lithosphere, (3) thermal structure of slabs in the upper mantle, and (4) velocity of slabs in the upper mantle. We denote non-dimensional variables with primes and non-dimensionalize lengths with respect to Earth radius (R_0, Table 1). Temperature is non-dimensionalized using $T = \Delta T(T' + T'_0)$, where ΔT is temperature drop and $T'_0 = T_0/\Delta T$ is surface temperature.

2.1. Plate history model

A prescribed time-dependent plate history model is required to guide the evolution of the lithosphere and mantle in numerical models with progressive data assimilation. The plate model describes the evolution of plate boundaries, plate velocities, oceanic lithosphere ages, continent boundaries (i.e., non-oceanic regions), velocities in deforming regions, and internal boundaries such as cratons. Typically the model has a temporal resolution of 1 Myr. We generate a simple synthetic regional plate history model to demonstrate the assimilation method and then use a global plate history model modified and extended back in time from Seton et al. (2012) to demonstrate the method in spherical convection models. We create a sequence of *a priori* data files using the plate

Table 1
Input parameters for *a priori* assimilation data files and convection models. † The second value applies to cases G2 and G3 only.

Parameter	Symbol	Value	Units
Slab radius of curvature	R_c	200	km
Slab depth	z_s	Variable	km
Slab dip	θ	45	degrees
Mantle temperature	T_m	1800/1700†	K
Surface temperature	T_0	300	K
Temperature drop	ΔT	1500/2800†	K
Lithosphere assimilation depth	z_l	64/ Eq. 4†	km
Lithosphere assimilation parameter	β	0.5	–
Maximum slab stencil depth	λ_{max}	350	km
Minimum slab stencil depth	λ_{min}	75	km
Maximum slab stencil smoothing	μ_{max}	75	km
Earth radius	R_0	6371	km
Core-mantle boundary radius	R_{cmb}	3505	km
Thermal diffusion coefficient	κ	10^{-6}	m^2s^{-1}
Thermal diffusion timescale	τ	1.286×10^6	Myr
Thermal age	A	Variable	Ma
Minimum thermal age	A_{min}	0.01	Ma
Subducting plate velocity	v_{sub}	5	cm/yr